N92-21925

A BURST FROM A THERMONUCLEAR RUNAWAY ON AN ONeMg WHITE DWARF

S. Starrfield[1,3] M. Politano[1,2], J. W. Truran[4], and W. M. Sparks[2]

[1]Department of Physics and Astronomy, Arizona State University, Tempe, AZ
[2]Applied Theoretical Physics Division, Los Alamos National Laboratory, Los Alamos, NM
[3]Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico
[4]Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, IL

ABSTRACT

We have performed studies which examine the consequences of accretion, at rates of $10^{-9}M_{\odot}yr^{-1}$ and $10^{-10}M_{\odot}yr^{-1}$, onto an ONeMg white dwarf with a mass of $1.35M_{\odot}$. In these studies, we used our Lagrangian, hydrodynamic, one-dimensional computer code that now includes a network with 89 nuclei up to ^{40}Ca, elemental diffusion, new opacities, and new equations of state. Our initial abundance distribution corresponded to a mixture that was enriched to either 25%, 50%, or 75% in products of carbon burning (Arnett and Truran 1969). The remaining material in each case is assumed to have a solar composition. The evolution of the thermonuclear runaway on the $1.35M_{\odot}$ white dwarf, with $M = 10^{-9}M_{\odot}$, produced peak temperatures in the shell source exceeding 300 million degrees. The sequence produced significant amounts of ^{22}Na from proton captures onto ^{20}Ne and significant amounts of ^{26}Al from proton captures on ^{24}Mg. This sequence ejected $5.2 \times 10^{-6}M_{\odot}$ moving with speeds from ~100km/s to ~2300km/s. When the mass accretion rate was decreased to $10^{-10}M_{\odot}$, the resulting thermonuclear runaway produced a shock that moved through the outer envelope of the white dwarf and raised the surface luminosity to $L > 10^{7}L_{\odot}$ and the effective temperature to values exceeding $10^{7}K$. The interaction of the material expanding from off of the white dwarf with the accretion disk should produce a burst of γ-rays.

I. Introduction

A classical nova outburst occurs on the white dwarf component of a close binary system which is a member of the general class of Cataclysmic Variables (hereafter, CV). In a CV, the secondary is commonly assumed to be filling its Roche Lobe and losing hydrogen-rich material through the inner Lagrangian point onto an accretion disk that surrounds the white dwarf primary. The physical process, which drives the secondary into filling its Roche Lobe, is still to be determined as is the physical process which removes angular momentum from the gas in the accretion disk and allows it to spiral onto the white dwarf. Other members of the class are dwarf novae, AM Her variables, intermediate polars, recurrent novae, and some of the symbiotic variables. Those systems in which the compact object is either a neutron star or a black hole are called low mass x-ray binaries (LMXRB's) and some of them may be the evolutionary consequences of the secular evolution of some classes of nova systems.

II. The Outburst and β^+-unstable Nuclei

In this paper, we concentrate on those explosions in which the compact object is a white dwarf. Theoretical studies have shown that a gradually accumulating shell of hydrogen-rich material on a massive white dwarf is unstable to a thermonuclear runaway (hereafter, TNR). The simulations of this evolution reproduce most of the observed features of the nova outburst. The calculations further imply that the energetics of the outburst, and thus the nova speed class, is sensitive to the abundances of the CNONeMg nuclei and also depends on the mass of the accreted shell, the white dwarf mass, and the accretion rate. The hydrodynamic calculations of the evolution of the TNR show that the early evolution is very slow and that the time scale is determined by the rate of accretion of material from the secondary onto the white dwarf. Once the temperature in the nuclear burning region reaches about 30 million degrees, a convective region forms above the region of peak temperature and slowly grows toward the surface. The rest of the evolution involves the interaction between the rapidly growing temperature in the nuclear burning region and convection, which continually mixes material in the nuclear burning region with the layers closer to the surface.

One of the most important results arising from the hydrodynamic simulations has been the identification of the role played by the four β^+-unstable nuclei: ^{13}N, ^{14}O, ^{15}O, and ^{17}F. As soon as the temperature in the shell source exceeds 10^8K, the abundances of these nuclei increase to where their presence severely impacts the nuclear energy generation in the envelope since every proton capture must now be followed by a waiting period before the β^+ decay occurs and another proton can be captured on the daughter nucleus. In addition, because of the existence of a convective region, which ultimately encompasses the entire accreted envelope, the most abundant of the CNO nuclei in the envelope at the peak of the outburst will be the β^+-unstable nuclei.

This has important and exciting consequences for the subsequent evolution. (1) Since the energy production in the CNO cycle comes from proton captures followed by a β^+-decay, the rate at which energy is produced, at temperatures exceeding 10^8K, depends only on the half-lives of the β^+-unstable nuclei and the numbers of CNO nuclei initially present in the envelope. This is because the CNO reactions do not create new nuclei, but only redistribute them among the various CNO isotopes (Starrfield, Truran, Sparks, and Kutter 1972; Truran 1982). (2) Since the convective turn-over time scale is usually about 10^2 sec near the peak of the TNR, a significant fraction of the β^+-unstable nuclei can reach the surface without decaying and the rate of energy generation at the surface will exceed 10^{12} to 10^{13} erg gm^{-1} s^{-1} (Starrfield 1989). This will produce a burst of γ-rays prior to optical maximum light. (3) Since convection operates over the entire accreted envelope, it brings unburned CNO nuclei into the shell source, when the temperature is rising very rapidly, and keeps the CNO nuclear reactions operating far from equilibrium.

Once peak temperature is reached and the envelope begins to expand, the simulations of the outburst, which include a detailed calculation of the abundance changes with time, show that the rate of energy generation declines only as the abundances of the β^+-unstable nuclei decline since their decay is neither temperature nor density dependent (see Starrfield 1989 for a detailed review). The numerical calculations performed with the CNO nuclei enhanced show that more than 10^{47} erg are released into the envelope after its expansion has begun and it will reach radii of more than 10^{10}cm before all of the ^{13}N has disappeared (Starrfield, Truran, and Sparks 1978; Starrfield and Sparks 1987). Finally, since these nuclei decay when the temperatures in the envelope have declined to values that are too low for any further proton captures to occur, the final isotopic ratios in the ejected material will not agree with those ratios predicted from studies of equilibrium CNO burning.

We predict that the large abundance of β^+-unstable nuclei at the surface, early in the outburst, will produce γ-ray emission. As mentioned above, the peak rate of energy generation in the surface layers can reach (or even exceed under some circumstances) $\sim 10^{13}$erg gm^{-1}s^{-1} from the decays of the β^+-unstable nuclei. This amount of energy is released in the outer layers which have a mass of $\sim 10^{22}$gm. Therefore, we estimate that the peak luminosity from the decays, which will appear primarily as 0.5Mev photons, could exceed 10^{35}erg s^{-1}. Of course, we realize that only those photons emitted within a layer that is less than ~ 1 γ-ray optical depth from the surface will actually appear as photons with these energies. The remaining photons will only be emitted after they have experienced a few scatterings. This means that we need to perform a Monte-Carlo simulation of this phase of the outburst in order to make useful predictions of the γ-ray and hard x-ray emission at this time. Nevertheless, an observation of γ-ray emission from a nova early in the outburst would strongly constrain, in our simulations, the extent of the convective region during the early phases of the explosion.

We emphasize that the results described in the last paragraph are based entirely on the hypothesis that, in order for an outburst to occur, the shell source must be sufficiently degenerate for the peak temperature to exceed 10^8K. If this is the case, and if convection is as efficient as predicted by normal stellar evolution modeling, then the effects of the β^+-unstable nuclei are inevitable. In addition, it is an observational fact that the abundances of the CNONeMg nuclei are enhanced in the ejecta of some novae (Truran 1990), and consequently they must also be enhanced in the nuclear burning region. Our simulations have shown that the presence of enhanced CNO nuclei in the envelope is required in order to produce a fast nova outburst. No calculation involving only a solar mixture has been successful in reproducing a realistic fast nova outburst and none of the observational studies of the elemental abundances in the ejecta reports that the material is of solar composition; the ejecta are always enriched in nitrogen and a number of other elements.

Theoretical calculations show that the evolution described above will release enough energy to eject material with expansion velocities that agree with observed values and that the predicted light curves produced by the expanding material can agree quite closely with the observations (see Starrfield 1989, 1990; Shara 1989; Truran, Starrfield, and Sparks 1992).

III. Oxygen-Neon-Magnesium Novae

In a companion paper in these proceedings, we discuss the observational and theoretical situation concerning γ-ray emission from the decay of ^{26}Al in the interstellar medium (Truran, Starrfield, and Sparks 1992). However, it is important to point out that the recent theoretical predictions of ^{26}Al production in nova outbursts (Nofar, Shaviv, and Starrfield 1991; Weiss and Truran 1990) critically depend on the existence of oxygen-neon-magnesium (hereafter, ONeMg) white dwarfs in nova systems. Therefore, in this section we review the observational evidence for such occurrences. ONeMg novae are one of the more important discoveries made with the **IUE** satellite, which has provided temporal coverage from **Einstein** to **GRO**. It has been discovered that there are two distinct composition classes of novae, those that occur on carbon-oxygen (CO) white dwarfs and those that occur on ONeMg white dwarfs.

If a CO nova is caught early enough in the outburst, an **IUE** spectrogram will show a continuum rising to the red, broken by what appear to be emission and absorption lines (see, for example, Starrfield 1990). However, the application of modern techniques in NLTE, spherical, expanding, stellar atmospheres, to these spectra of novae (Hauschildt et al. 1992), have shown that the spectral features are all caused by overlapping absorption lines of Fe II. The "emission" lines are, in reality, regions of transparency in these overlapping lines.

In contrast, fast ONeMg novae show a very hot continuum at maximum plus emission lines, which can be identified as characteristic of a low density gas. The speed of decline of such a nova also implies that fast ONeMg nova outbursts occur on very massive white dwarfs with small envelope masses. However, early spectra of QU Vul 1984, the only slow ONeMg nova studied in outburst with the **IUE** satellite, show features similar to those of CO novae (Stryker et al. 1988; Hauschildt et al. 1992).

A recent ONeMg nova occurred in the LMC in 1990 and exhibited outburst behavior very similar to that of the galactic ONeMg nova V693 CrA 1981 (Williams et al. 1985; Sonneborn, Shore, and Starrfield 1990). The initial **IUE** spectra, shown in Figure 1, were obtained over a period of a few days. The date of observation is given on each panel. One

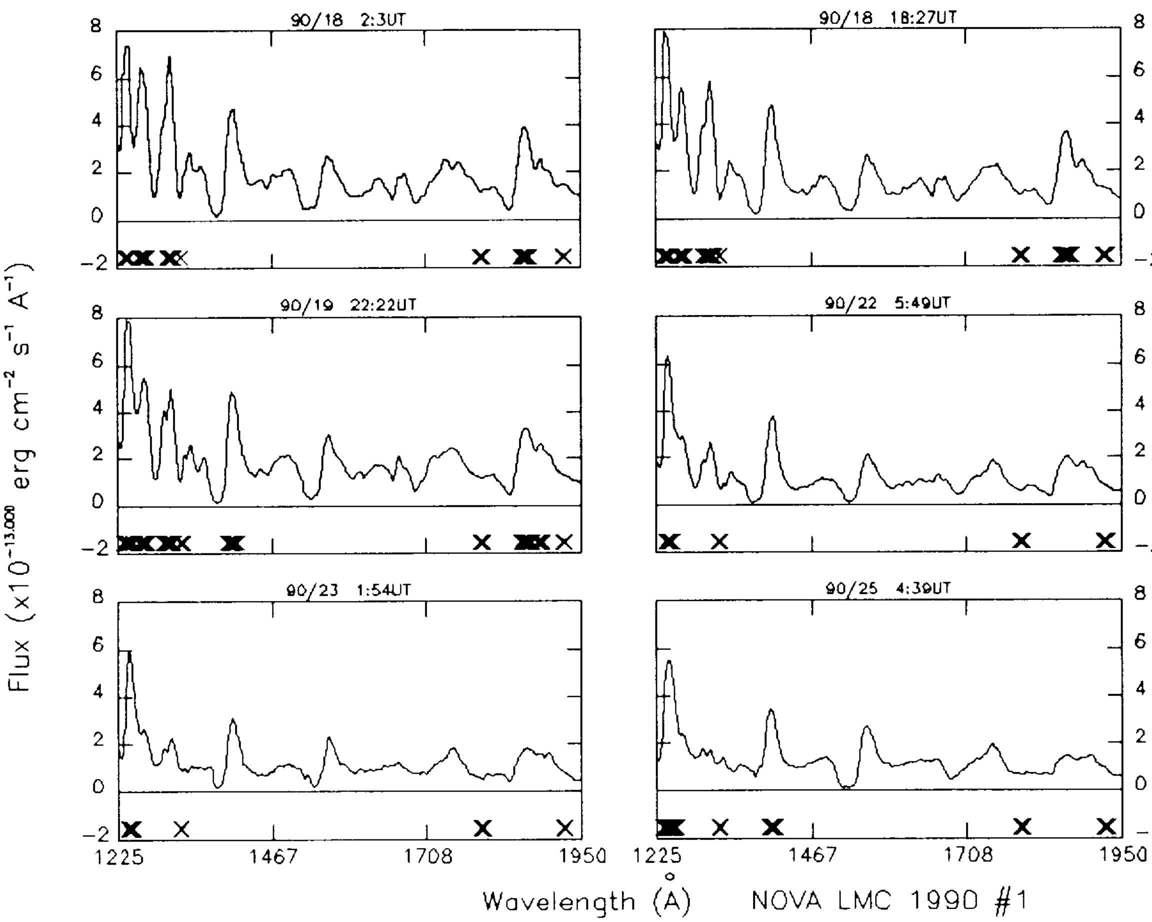

Figure 1. A montage of early spectra of Nova LMC 1990 #1 obtained with the **IUE** satellite early in the outburst. The date and time that each spectrum was obtained are listed on top of each spectrum.

can identify a hot continuum and emission lines from N V, Si IV, C IV, and Al III. All of the strong lines exhibited P-Cygni profiles, with flat-bottomed absorption troughs extending to more than -6000 km s^{-1}. There is no resemblance to early spectra of slow CO novae (Stryker et al. 1988; Hauschildt et al 1992). Analysis of these spectra indicate that fast ONeMg novae do not eject much material and that the expanding shell has become optically thin in the lines at maximum light (Sonneborn, Shore, and Starrfield 1990).

The optical spectra obtained by Dopita and Rawlings (1990; IAUC 4964) provided additional evidence that LMC 1990 #1 was an extragalactic analog of V693 CrA and, thereby, an ONeMg nova. They reported that [Ne III] 3868Å appeared on 22 January, and [Ne V] 3426Å on 29 January. By 13 February 1990, [Ne V] was the strongest emission feature in the optical spectrum. The ultraviolet forbidden neon lines seen at late stages in other ONeMg novae ([Ne IV] 1602Å and 2420Å) were not detected in the **IUE** spectra. This is not surprising, since they did not appear in either V693 CrA or QU Vul until well into the nebular stage, when the densities in the ejecta had dropped by a large factor from the values determined at maximum light. Finally, the ultraviolet light curve suggests that the luminosity in the wavelength region from 1200Å to 3300Å reached a value of 3 x 10^{38} erg s^{-1} at maximum brightness. This value assumes a distance to the LMC of 55 kpc and shows that the luminosity in this nova exceeded the Eddington luminosity for a $1.0M_{\odot}$ white dwarf.

IV. A Burst From Accretion onto an ONeMg White Dwarf

Given both the existence of ONeMg white dwarfs and the success of the one-zone nucleosynthesis calculations (Weiss and Truran 1990; Nofar, Shaviv, and Starrfield 1991), it becomes appropriate to examine the consequences of accretion of hydrogen rich material onto such a white dwarf. We have done this, using our one dimensional hydrodynamic computer code which incorporates a large nuclear reaction network to follow the changes in abundance of 89 nuclei (Kutter and Sparks 1972; Weiss and Truran 1990; Nofar, Shaviv, and Starrfield 1991; Politano et al. 1991a). A detailed description of the current version of this code will appear elsewhere (Politano et al. 1991a). Here, we briefly discuss one set of calculations.

In our most recent studies of the accretion of hydrogen-rich material onto white dwarfs, we have varied both the white dwarf mass (Politano et al. 1991a) and the amount of enriched material (Politano et al. 1991b). Table 1 presents the results for accretion onto $1.35M_{\odot}$ white dwarfs for the 4 evolutionary sequences discussed in Politano et al (1991b), where we have both varied the amount of ONeMg material assumed to have been mixed up into the accreted layers (Sequences 1, 2, and 3) and, in addition, decreased the rate of mass accretion from 1.6 x $10^{-9}M_{\odot}$ (Sequences 1, 2, and 3) to 1.6 x $10^{-10}M_{\odot}$ (Sequence 4). Here we concentrate on Sequence 4 which produced a burst of γ-rays.

This sequence accretes at a rate of 1.6 x $10^{-10}M_{\odot}$ for 3 x 10^{5}yr until it has accumulated an accreted envelope with a mass of nearly 5 x $10^{-5}M_{\odot}$. At this time, the temperature at the interface between the accreted and core layers (hereafter, CEI) exceeds 80 million degrees and we end the accretion phase of the evolution. The temperature continues to rise, but slowly, initially, since a significant fraction of the hydrogen at these depths has been burned. However, a convective region has formed above the CEI and is slowly moving into layers closer to the surface, where there is still a significant abundance of hydrogen. As soon as the convective region reaches this hydrogen, it is mixed down to the CEI, where the temperature has grown to ~200 million degrees. The addition of fresh fuel to the shell source causes the temperatures and rates of energy production to increase precipitously. Over the next .01 s, the rate of energy generation flashes to 1.36 x 10^{20}erg gm^{-1} s^{-1} and the temperature reaches 623 million degrees.

This high a temperature causes a significant overpressure in these layers and a pressure wave begins to move both inward and outward. As this wave moves outward, it produces a deflagration which causes a marked increase in the rate of energy generation and temperature in each zone. For example, the CEI is at zone 60 and, by the time the deflagration has reached to zone 70, the temperature exceeds 762 million degrees and ϵ_{nuc} ~ 7.1 x 10^{20} erg gm^{-1} s^{-1}. Even at zone 80, the temperature still exceeds 640 million degrees and ϵ_{nuc} exceeds 5.5 x 10^{20} erg gm^{-1} s^{-1}. The deflagration continues to move outward and we show, in Figures 2 through 5 the observable effects of this phenomenon on the surface layers. Figure 2 is the light curve, which shows that the luminosity rapidly grows to 2 x $10^7 L_\odot$ as the effective temperature climbs to 6.5 x 10^6K (Figure 4). As the deflagration passes through the surface layers, it causes ϵ_{nuc} near the surface to increase to values exceeding 4 x 10^{17} erg gm^{-1} s^{-1}. However, unlike our earlier discussion about other evolutionary sequences, the energy is not being produced by β^+ decays but rather by (p,γ) reactions on the abundant nuclei. We are now trying to determine the time scale of this burst, and will model the emission in the outer layers with a Monte-Carlo investigation of the γ-ray photon transport.

Once this deflagration has passed through the outer layers, the intense heating causes the velocities to increase to values exceeding 19,000 km s^{-1}. The accelerations are very large and the rise to this velocity takes only a small fraction of a second. The layers begin to

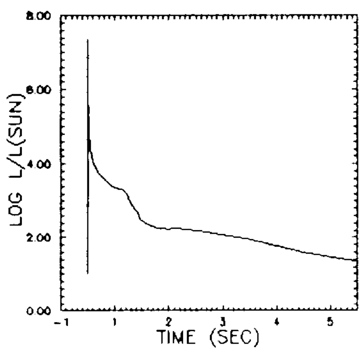

Figure 2. The luminosity as a function of time at shock break out.

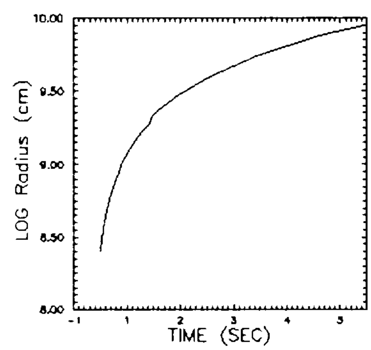

Figure 3. The radius as a function of time at shock break out.

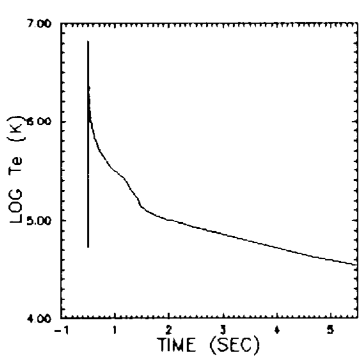

Figure 4. The effective temperature as a function of time.

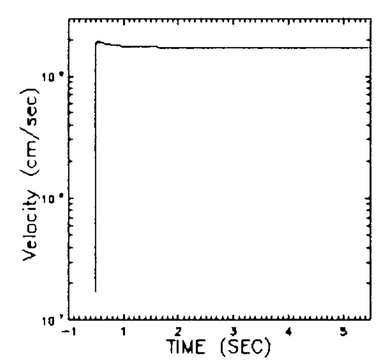

Figure 5. The velocity as a function of time at shock break out.

expand and reach radii of 10^{10}cm within a few seconds (Figure 3). By this time, 5 x $10^{-7} M_\odot$ have been ejected in a shell with most of the material moving at speeds exceeding $\sim 10^4$ km s^{-1}. We continued this evolution and will report on the final results elsewhere.

TABLE 1
EVOLUTIONARY RESULTS

Sequence	1	2	3	4
MASS ($M_\odot$)	1.35	1.35	1.35	1.35
ONeMg (% mf)	25	50	75	75
$L/L_\odot$ (10^{-3})	9.60	9.60	9.60	9.60
T_{eff} (K)	30,300	30,300	30,300	30,300
Radius(km)	2488.	2488.	2488	2488.
M ($10^{-9} M_\odot yr^{-1}$)	1.6	1.6	1.6	0.16
τ_{TNR} (10^3 yr)	3.3	4.6	11.3	304.7
M_{acc} ($10^{-5} M_\odot$)	.53	.73	1.8	4.8
$\epsilon_{nuc\text{-}MAX}$ (10^{17})	.19	1.1	3.9	7080.
T_{PEAK} (10^6K)	257	302	390	762
$T_{eff\text{-}MAX}$ (10^5K)	3.40	6.42	9.02	65.4
M_{ej} ($10^{-6} M_\odot$)	0.0	.36	15.0	.5
V_{max}(km s^{-1})	110	240.	3360	19,400.

Although this has been the most intense burst that we have produced to date in our evolutionary studies of accretion onto white dwarfs, it does not qualify as a γ-ray burst since the peak conditions are really in the hard x-ray regime. However, we must emphasize that our treatment of the surface boundary is characteristic of a normal stellar evolution code and assumes equilibrium conditions. Any non-equilibrium effects will probably act to increase the temperatures and luminosities that are produced in this event. In addition, it is also appropriate to consider the systems in which we have assumed this evolution was occurring. Since this is a white dwarf in a CV system, it should be surrounded by an accretion disk. It then becomes necessary to ask what the consequences will be of the collision of the expanding material with the accretion disk. We also note that the material within the accretion disk is moving at supersonic speeds and the interaction will produce a strong oblique shock. It appears to us that we will have to do some fairly sophisticated modeling to follow the passage of the expanding layers of the white dwarf through the accretion disk;

here, we note only a few important considerations.

First, the time scale of the burst will be broadened by the time it takes the expanding layers to pass through the accretion disk. At the speeds predicted by the simulation, 19,000 km s^{-1}, it should lengthen the time scale of the burst to a few seconds, instead of the fractions of a second seen in Figure 2. Second, the post shock temperature of an ideal gas moving with speeds of 19,000 km s^{-1} exceeds 4 x 10^9K or ~300keV (Kaplan 1966) while, if we use the development of Brecher, Ingham, and Morrison (1977) for a shock passing through a low density envelope, we arrive at a value of ~850keV. In either case, such a strong shock moving through the low density accretion disk will produce and radiate very high energy photons. This certainly does represent a burst of γ-rays, although it is not a γ-ray burst.

V. Summary and Discussion

In this paper, we have first described the evidence for the existence of nova outbursts occurring on ONeMg white dwarfs and then presented the results of hydrodynamic simulations of the consequences of accretion of hydrogen-rich material onto such white dwarfs. These studies involved accretion onto $1.35M_\odot$ ONeMg white dwarfs at either $\sim 10^{-9}M_\odot yr^{-1}$ or $\sim 10^{-10}M_\odot yr^{-1}$. Either value is in reasonable agreement with the observations. We found that as we increased the heavy element abundance, and thereby reduced the hydrogen abundance, both the accretion time scale and the accreted mass increased. Our sequence with a lower rate of accretion accreted a factor of three more material than the equivalent sequence done with the larger mass accretion rate. This is because the envelope temperatures grew more slowly since there was a smaller amount of accretion heating and more time for the compressional energy to be radiated.

One sequence was so degenerate, at the time of the thermonuclear runaway, that a shock was initiated at the core-envelope interface; when this shock reached the surface of the white dwarf it produced a burst of high energy photons. It also accelerated the surface layers to speeds of ~19,000 km s^{-1}. The peak luminosity exceeded $10^7L_\odot$ and, simultaneously, the peak T_{eff} exceeded 6 million degrees. Although these conditions alone are not necessarily appropriate for the production of a strong γ-ray burst, we note that in fact, we can expect the expanding layers to collide both with the accretion disk and with the secondary star, which has been supplying the hydrogen rich fuel for the outburst. Simple estimates of the peak temperature that should obtain in this interaction suggests that it could exceed 500 keV. This would produce a very luminous burst of γ-ray photons over a time scale of a few seconds. The fact that such a burst was, apparently, not observed by **GRO** during the July outburst of Nova Sgr 1991 implies either that such an event cannot accompany all ONeMg nova outbursts or that the nova was behind the earth at the appropriate time (Shrader 1991, private communication).

We are grateful to a number of our colleagues for valuable discussions and assistance. We would especially like to thank S. Shore and G. Sonneborn for allowing us to display spectra of LMC 1990 #1 prior to publication and providing us with the IDL programs that prepared the montage of spectra. We would also like to thank P. Hauschildt, J. Krautter, I. Nofar, G. Shaviv, C. Shrader, and R. Wehrse for their help. This work was supported in part by NSF and NASA grants to the University of Illinois and Arizona State University and by the DOE.

REFERENCES

Arnett, W. D., and Truran, J. W. 1969, *Ap.J.*, **157**, 339.

Hauschildt, P. H., Wehrse, R., Starrfield, S., and Shaviv, G. 1992, *Ap.J.*, in press.

Kaplan, S. A. 1966, *Interstellar Gas Dynamics* (Oxford: Pergamon).

Kutter, G. S., and Sparks, W. M. 1972, *Ap. J.*, **175**, 407.

Nofar, I., Shaviv, G., and Starrfield, S. 1991, *Ap.J.*, **369**, 440.

Politano, M., Starrfield, S., Truran, J. W., Sparks, W. M., and Weiss, A. 1991a, in preparation.

Politano, M., Starrfield, S., Truran, J. W., Sparks, W. M. 1991b, in preparation.

Shara, M. M. 1989, *Pub. Ast. Soc. Pac*, **101**, 5.

Sonneborn, G., Shore, S. N., and Starrfield, S. 1990, in *Evolution in Astrophysics: IUE Astronomy in the Era of New Space Missions*, ed. E. Rolfe (ESA SP-310; Noordwijk), p. 439.

Starrfield, S. 1989, in *Classical Novae*, ed. N. Evans and M. Bode (New York: Wiley), p. 123.

Starrfield, S. 1990, in *Evolution in Astrophysics: IUE Astronomy in the Era of New Space Missions*, ed. E. Rolfe (ESA SP-310; Noordwijk), p. 101.

Starrfield, S., Truran, J. W., and Sparks, W. M., 1978, *Ap. J.*, **226**, 186.

Starrfield, S., Truran, J.W., Sparks, W.M. and Kutter, G. S. 1972, *Ap. J.*, **176**, 169.

Starrfield, S., and Sparks, W. M. 1987, in *Cataclysmic Variables. Recent Multifrequency Observations and Theoretical Developments*, ed. H. Drechsel, Y. Kondo, and J. Rahe, (Dordrecht: Reidel), p. 379.

Stryker, L. L, Hestand, J., Starrfield, S., Wehrse, R., and Shaviv, G. 1988, in, *A Decade of UV Astronomy with the IUE Satellite*, ed E. Rolfe (Noordwijk: Estec Publications: SP-263), p. 149.

Truran, J. W. 1982, in *Essays in Nuclear Physics*, eds. C. A. Barnes, D. D. Clayton and D. N. Schramm (Cambridge: Cambridge U. Press), p. 467.

Truran, J. W. 1990, in *The Physics of Classical Novae*, ed. A. Cassatella and R. Viotti, (Heidelberg: Springer-Verlag), p. 373.

Truran, J. W., Starrfield, S., and Sparks W. M. 1992, these proceedings.

Weiss, A. and Truran J. W. 1990, *A&A*, **238**, 178.

Williams, R.E., Ney, E.P., Sparks, W.M., Starrfield, S., Truran, J.W. 1985, *M.N.R.A.S.*, **212**, 753.